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INVESTIGATION OF DC-8 NACELLE MODIFICATIONS TO REDUCE FAN-COMPRESSOR NOISE IN AIRPORT COMMUNITIES

Part VI – Psychoacoustic Evaluation

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16. Abstract

Nacelle modifications intended to reduce fan-compressor noise emitted from DC-8-50/61 airplanes were fabricated and flight tested. Subjective reaction to the flyover noise of these nacelle modifications was assessed by asking 41 college students to judge the acceptability of the sound of existing and modified aircraft as reproduced in an anechoic chamber. The method of constant stimulus differences was used to assess pairs of stimuli. Each pair consisted of one recording from each aircraft. Sounds recorded outdoors and indoors were included. Operational conditions were tested that represented takeoff, reduced-climb-gradient, and landing-approach thrusts at nominal heights ranging from 500 to 2500 feet.

The most important findings were:

1. Improvements were noted for all heights and thrusts investigated.
2. For the landing-approach thrust condition, the judged improvement in the noise due to the installation of modified nacelles ranged from 11 to 14 EPNdB over the range of heights investigated.
3. The effective-perceived-noise-level noise-rating scale adequately assessed the improvement in acceptability.

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SUMMARY

In May 1967, the NASA initiated a program with the McDonnell Douglas Corporation to investigate turbofan-engine nacelle modifications designed to reduce fan-compressor noise from the JT3D engines on DC-8-50/61 aircraft. The program was directed at the definition of nacelle modifications that could reduce the perceived noise level by 7 to 10 PNdB under the landing-approach path, but with no increase in takeoff noise. The program was conducted in five phases: (1) nacelle design studies and duct-lining investigations, (2) ground static tests of noise suppressor configurations, (3) flyover-noise and cruise-performance tests of a selected modification design, (4) studies of the economic implications of retrofit of the modification, and (5) an evaluation of human response to the flyover noise of the modified nacelles. This document reports the results of the fifth phase of the program. Goals of this phase were assessment of (a) the increase in acceptability of aircraft flyovers due to the nacelle treatment as determined by human judgments and (b) the relationship of various rating scales to these human judgments.

To assess the subjective effects of the change in flyover noise due to the nacelle modifications, 41 college students were asked to listen to several pairs of recorded flyover noises reproduced in an anechoic chamber. Each pair of sounds consisted of the flyover noise, for similar operational conditions, produced by the existing aircraft and by the modified aircraft. Had the pairs of sounds been presented at the true levels recorded during the flyovers, the subjects would have judged the modified airplane more acceptable for all operational conditions investigated. Therefore, in order to obtain a quantitative measure of the improvement, the relative levels between the two sounds in the pairs were artificially varied in a predetermined manner. The relative increase in the noise level of the modified airplane that was found to be required for equal acceptability was designated the judged improvement.

Judged improvement was the basic dependent variable. The independent variables were the flight conditions of the selected flyover noise recordings. There were 18 recordings selected from those obtained outdoors and 6 recordings selected from those obtained indoors under the flight path during the flyover noise tests. These 24 recordings were used to make up the various pairs of sounds. The outdoor noise recordings consisted of nine recordings of the noise from the existing and nine from the modified aircraft at nominal heights overhead of 500, 1000, and 2500 feet for each of the three engine power settings of landing-approach thrust, takeoff thrust, and reduced-climb-gradient thrust. The indoor noise recordings consisted of three recordings of the noise from the existing and three from the modified aircraft at nominal heights of 500 feet for landing-approach thrust, 1500 feet for takeoff thrust, and 2500 feet for the reduced-climb-gradient thrust.

Judgments of the improvement in acceptability were compared to improvements calculated from sound pressure levels determined from the recordings. Comparisons were made between judged improvement and improvements indicated by eight noise-rating scales that have been used or proposed for use in evaluating aircraft flyover noise. Statistical analyses of the differences between judged improvements and improvements indicated by the rating scales were conducted to assess the ability of the scales to predict the judged improvements.

Over the range of nominal heights from 500 to 2500 feet, the judged improvements in the acceptability of the sounds recorded outdoors varied from approximately 11 to 14 EPNdB at the landing-approach power setting, from approximately 4 to 13 EPNdB at the reduced-climb-gradient power setting, and from approximately 4 to 7 EPNdB at the takeoff power setting. For the indoor noise recordings, the judged improvements were approximately 8.5 EPNdB at the landing-approach power setting, approximately 5.5 EPNdB at the reduced-climb-gradient power setting, and approximately 4.5 EPNdB at the takeoff power setting.

The differences between the judged improvements and the improvements indicated by the effective-perceived-noise-level noise-rating scale were on the order of 2 to 3 EPNdB, although differences ranging from –5 to +6 EPNdB were noted.

The statistical analyses of the eight noise-rating scales investigated indicated that none of the eight scales was significantly superior to the effective-perceived-noise-level noise-rating scale in predicting the judged improvements.

INTRODUCTION

The growth of the air transportation industry and the increase in the number of people living in communities around airports have increased human annoyance due to operations of commercial jet transports. This increased annoyance has stimulated efforts to find means to alleviate the problem through reducing the level of the noise radiated from airplanes, through modifying airplane operational procedures, and through achieving compatible usage of the land around airports. The alleviation efforts are being conducted as part of a coordinated industry-government research program.

In May 1967, the Langley Research Center of the NASA contracted with the McDonnell Douglas Corporation and The Boeing Company to investigate nacelle modifications for operational Douglas and Boeing transports powered by Pratt & Whitney Aircraft (P&WA) JT3D turbofan engines. The nacelle modifications were to achieve significant reductions in flyover noise levels in airport communities located under landing-approach flight paths.

During landing approach, the perceived noisiness and hence the annoyance caused by sound from the JT3D engines is attributed principally to the discrete-frequency tones radiated from the fan stages through the inlet and fan-exhaust ducts. Accordingly, the purpose of the McDonnell Douglas and the Boeing investigations was to develop methods of suppressing fan noise. The McDonnell Douglas investigation was directed toward the determination of nacelle modifications that could suppress fan noise primarily through the use of fan-inlet ducts and short fan-exhaust ducts containing acoustically absorptive materials. The modifications were to be applicable to DC-8 airplanes equipped with short-duct nacelles, that is, to the series 50 and the model 61 airplanes.

The McDonnell Douglas goal was a 7 to 10 PNdB reduction in the outdoor perceived noise level (PNL) under the landing-approach path. The goal was stated in terms of PNL because that measure of human annoyance due to noise was in wide use at program initiation. As the program proceeded, increasing interest developed in assessing the noise reduction in terms of effective perceived noise level (EPNL). This measure includes allowances for the annoyance due to pure tones in the noise spectra and due to the duration of the noise. The flight-test program was therefore planned to obtain the data needed to permit assessment of the noise reductions in terms of EPNL. In addition, it was required that the nacelle modifications be designed to satisfy the following requirements:

- No adverse effect on takeoff or climbout noise
- No compromise with flight safety
- No additional flight-crew workload
- Retroactively modified airplanes to be economically viable.

In seeking economic viability, efforts were to be made to minimize changes in existing nacelle or pylon structure and equipment.

The McDonnell Douglas program is reported in six parts: Part I, a summary of the major results of the program (ref. 1); Part II, a report of the initial nacelle modification design studies and duct-lining investigations (ref. 2); Part III, a report of static tests of noise suppressor configurations (ref. 3); Part IV, a flight evaluation of the acoustical and performance effects of the selected design of modified nacelles on a DC-8-55 airplane (ref. 4); Part V, a study of the economic implications of retrofitting the selected design (ref. 5); and Part VI, an evaluation of human response to the flyover noise of the modified nacelles (presented in this document). The results of the Boeing program are reported in reference 6.

The primary objective of the psychoacoustic tests was to determine, through the use of human judgments, the change in acceptability of the sound from the DC-8 when equipped with the acoustically treated nacelles. Noise from existing and modified airplanes differed principally in the strength of the discrete-frequency components in the spectrum of the noise perceived during a flyover. Figure 1 shows the modified nacelle as installed in the DC-8-55 test airplane.

The judgment data in this program were obtained by the method of constant stimulus differences. This test method was chosen to facilitate comparison of the results obtained in this study to those obtained by other investigators (e.g., refs. 7 to 10). The psychoacoustic tests used duplicates of tape recordings made during the flyover-noise tests conducted at Fresno, California (ref. 4).

Recordings were made at locations under the airplane flight path. For each aircraft, nine recordings were included from various outdoor noise-recording stations and three from inside a house. The primary independent variables for the test were the engine power settings and the heights of the airplane over the noise-recording stations.

A second objective of the psychoacoustic evaluation was the comparison of human judgments to the improvement in acceptability as determined by eight noise-rating scales of current interest. These comparisons were required to assess the confidence to be placed in the use of the PNL and EPNL data reported in reference 4 as descriptors of human judgments. The decision to examine the six additional noise-rating scales, rather than limiting the investigation to PNL and EPNL, was made to broaden the scope of the investigation and to provide a statistical comparison of scales that have been used or proposed for aircraft noise evaluations. The additional scales were maximum instantaneous A-weighted sound level [dB(A)], maximum instantaneous C-weighted sound level [dB(C)], maximum instantaneous D-weighted sound level [dB(D)], maximum instantaneous perceived noise level together with a duration-correction factor (PNLM + D), maximum instantaneous tone-corrected perceived noise level (PNLTM), and maximum instantaneous loudness level (LL). Calculation procedures are defined in reference 11 for PNLM, PNLTM, PNLM + D, and EPNL; in reference 12 for dB(A) and dB(C); in reference 13 for dB(D); and in reference 14 for LL. These noise-rating scales were developed using bands of noise and discrete-frequency tones (refs. 15 to 18) and were later applied to ratings of the acceptability of a variety of noises (refs. 7 to 10). However, their applicability to the specialized group of noises used in this test was uncertain.

The indoor noise recordings were supplemented by simultaneous recordings made at a location just outside the house (fig. 2). These simultaneous recordings were used to determine the noise reduction afforded by the structure of the test house. The noise reduction of the test house was then compared to values of noise reduction previously measured and proposed for use in evaluation of aircraft noise in communities around airports.

McDonnell Douglas was responsible for directing and monitoring the psychoacoustic evaluations as well as providing duplicates of the outdoor noise recordings, conducting the statistical analyses, and interpreting the results. As a subcontractor, Stanford Research Institute, Menlo Park, California, under the direction of Karl D. Kryter and Frank R. Clarke, acquired the flyover noise recordings inside and outside the house, prepared the psychoacoustic test tapes, and conducted the psychoacoustic tests.

SYMBOLS

dB(A)	maximum instantaneous A-weighted sound level, decibels (dB)
dB(C)	maximum instantaneous C-weighted sound level, dB
dB(D)	maximum instantaneous D-weighted sound level, dB
D	duration-correction factor, dB
EPNL	effective perceived noise level, effective perceived noise decibels (EPNdB)
LL	maximum instantaneous loudness level, phons
PNL	instantaneous perceived noise level, perceived noise decibels (PNdB)
PNLM	maximum instantaneous perceived noise level, PNdB
PNLM+D	sum of the maximum instantaneous perceived noise level and the duration-correction factor, PNdB
PNLT	instantaneous tone-corrected perceived noise level, PNdB
PNLTM	maximum instantaneous tone-corrected perceived noise level, PNdB
PSE	point of subjective equality, dB
SPL	sound pressure level, dB re 0.0002 dynes/sq cm

METHODS AND APPARATUS

Experimental Design

The method of constant stimulus differences (paired comparisons) was utilized for this experiment. This method can be used to estimate subjective equality between two stimuli which differ in some characteristic or dimension. Subjects are asked to make judgments of one stimulus being "better than," "greater than," "less annoying than," or, in this case, "more acceptable than," some other stimulus. The basic test procedure consists of pairing one stimulus, called the standard stimulus, with each of a series of comparison stimuli presented at several levels above and below the standard stimulus. The percent of judgments associated with each of the levels of the comparison stimulus is then determined. The stimulus level required to yield 50 percent of the judgments "more acceptable than" and thus 50 percent of the judgments "less acceptable than" is obtained and denoted the point of subjective equality (PSE). (For a further discussion of psychophysical methods, see ref. 19.)

Thus, for this study, subjective improvement was defined as the amount that the noise emanating from the aircraft with modified nacelles would have to be increased to be judged equal to the noise emanating from the aircraft with existing nacelles. The PSE was obtained, in the general case, by using the noise of the existing aircraft as a standard stimulus and the noise of the modified nacelle aircraft as the comparison stimulus. In order to present the comparison stimulus at levels both above and below that of the standard stimulus, the noise of the modified aircraft was amplified to provide four levels, one each as ±1.5 and ±4 dB from an estimate of the PSE.

In designing the experiment, several precautions were taken to minimize causes of experimental bias. Bias related to the order of stimulus presentation was counterbalanced by presenting all pairs of stimuli in both orders; i.e., the sound of the existing nacelles followed by the sound of the modified nacelles and vice versa. Bias associated with the choice of which sound was used as the comparison stimulus was controlled by using the sound of the modified nacelles as the comparison stimulus for half the judgments and the sound of the existing nacelles as the comparison stimulus for the other half of the judgments. Bias associated with raising the level of the sound of the modified nacelles was assessed by repeating part of the test using stimulus pairs where the level of the sound of the existing nacelles was decreased. For this partial test replication, the sounds from the outdoor noise recordings for the three heights at the landing-approach thrust condition were used. Bias due to the order of presentation of the stimulus pairs was minimized by presenting the stimulus pairs in a random order.

The experimental design required a total of 120 pairs of stimuli comprised of:

1. Outdoor noise recordings: three heights, three thrusts, four levels of the comparison stimulus, and two orders of presentation (a total of 72 pairs).

2. Outdoor noise recordings used for the repeated tests: three heights, one thrust, four levels of the comparison stimulus, and two orders of presentation (a total of 24 pairs).

3. Indoor noise recordings: three thrusts at three separate heights, four levels of the comparison stimulus, and two orders of presentation (a total of 24 pairs).

Choice of Flyover-Noise Recordings

During the flyover noise evaluation (ref. 4), the noise recordings were screened to assure that they were not overloaded and did not contain significant extraneous noises. Approximately 440 acceptable recordings were identified. These recordings represented various thrusts, heights, aircraft weights, microphone locations, etc. From these recordings, it was decided to select the 18 outdoor recordings for the phychoacoustic tests. Nine recordings were selected for the existing and nine for the modified aircraft. The flight conditions included three engine power settings at each of the three nominal heights overhead. The three engine power settings were landing-approach thrust, reduced-climb-gradient thrust, and takeoff-rated thrust. The nominal heights were 500, 1000, and 2500 feet.

Six recordings were also selected from those made inside a house located under the flight path. From these, three indoor noise recordings were selected for the existing and three for the modified aircraft. The flight conditions for these indoor recordings were nominal heights of 500 feet for the landing-approach thrust, 2500 feet for the reduced-climb-gradient thrust, and 1500 feet for the takeoff-rated thrust.

Factors considered in the selection of the specific sample of outdoor noise recordings were: close agreement between the single-point EPNL values and the generalized EPNL calculations for corresponding flight conditions (ref. 4, fig. 38), existence of a group or cluster of data points with similar EPNL values and flight conditions, and similarity of flight conditions for existing and modified aircraft flyover recordings. Flight conditions and EPNL values for the selected recordings are given in table I.

Duplicates of the selected recordings were made. The maximum recording level during duplication was monitored to ensure that it was at least 10 dB below the distortion limit of the tape recorder. Pistonphone calibrations at a reference SPL of 124 dB at 250 Hz were provided so that actual SPL's could be determined. Calibration tones at several frequencies between 50 and 10 000 Hz were provided to determine frequency response corrections for the record/playback system exclusive of the microphone. Microphone response corrections were negligible.

The house inside which the indoor noise recordings were made was located under the aircraft flight path in a relatively isolated, rural agricultural area. It was a single-story, single-family residence, approximately 40 years old at the time of the tests. The house was built over a raised concrete slab with a crawl space beneath the slab. The walls of the house were made from 8-inch-thick solid concrete blocks, painted on the outside. There was a low attic over the ceiling with fiberglass insulation laid on the floor of the attic between the wooden ceiling joists and extending part way up between the roof rafters. The interior side of the concrete blocks was plastered and painted. There was a high painted-plaster ceiling over the rooms of the house.

Recordings were simultaneously made inside a front corner bedroom and outside the bedroom in the front yard. There were two dressers and two single beds in the bedroom. The microphone in the bedroom was placed approximately five feet above the hardwood, uncarpeted floor, on top of a dresser in the corner and away from the walls. The bedroom door was closed during the recordings. There were four windows in the bedroom, each fitted with window shades and light-weight drapes. Each window contained two double-hung sashes with four panes per sash. There were no storm windows installed. All windows in the bedroom were closed during the flyover test.

The differences between the SPL's recorded outdoors and the SPL's recorded indoors were examined to compare the noise reduction of the test house to other house noise-reduction measurements. Figure 3(a) presents a comparison of the Fresno house noise reductions to noise reductions measured for two houses at Wallops Station (ref. 20). The data for the house at Fresno were similar to those for a house with wood siding and slightly lower than those for a house with brick veneer facing.

Figure 3(b) compares the Fresno data to those contained in the proposed Aerospace Information Report AIR 1081 prepared by the Society of Automotive Engineers' Committee A-21. The Fresno data are similar to the data obtained for structures located near Los Angeles International Airport, but are lower than the proposed average data because the average data include measurements of the noise reduction of structures with more massive construction and more insulation than houses in Fresno or Los Angeles.

It is concluded that the noise reduction of the Fresno test house was not significantly different from the noise reduction of other houses typical of temperate climates. Flyover noise recordings made within this house were therefore considered acceptable for the test. Specific recordings were selected in a manner similar to that used for selection of outdoor recordings.

Test Tape Preparation

Only that portion of a flyover noise recording was used that was within 15 dB(C) of the maximum value, as read on a sound level meter set on the C-weighting scale. The noises on the test tape were all recorded at a level that yielded maximum signal-to-noise ratio and minimum distortion.

The two noises in each stimulus pair were separated by a 4-second interval. Pairs were separated by a 6-second interval during which the subjects recorded their responses and the experimenter read an identifying number for the next flyover pair. The durations of recordings ranged from 12 to 66 seconds.

Anechoic Chamber and Audio Equipment

The anechoic chamber used for the test had 21-inch-long fiberglass wedges on all six surfaces. The internal dimensions of the chamber, measured from the tips of the wedges, were 8.5 x 17.75 x 8 feet. The overall background noise level in the chamber was at least 30 dB below the peak level of the quietest of the flyover noise recordings. As indicated in figure 4, the chamber could accommodate as many as eight subjects. The subjects were seated along two arcs with a spacing of 3 feet between subjects.

A block diagram of the audio equipment used for reproducing the test stimuli is shown in figure 5. The equalization network was used to minimize variations in the frequency response of the loudspeakers as installed in the chamber. The step attenuator was used during the test to adjust the level of the signal from the tape recorder. These level adjustments were required in order to present the standard stimulus in each stimulus pair at the desired level and to adjust the level of the comparison stimulus to the values of 1.5 dB and 4 dB above and below the estimated PSE. The low-pass filter, 3 dB down at 8000 Hz, was used to minimize tape hiss. The loudspeakers, in two enclosures, were arranged vertically as shown in figure 4.

Calibration

The response of the loudspeakers in the chamber was initially equalized using wide-band white noise and 1/1-octave-band analyses of the SPL's. A constant-amplitude pure-tone sweep from 50 to

8000 Hz was then played through the system to examine the variability of the resultant sound field due to the characteristics of the loudspeakers. Seating arrangements were then established and the response to the wide-band noise and pure tones was measured at each listening position. For each of these response measurements, the microphone was placed at the head position, ear high, while the other seven positions were occupied by listeners. This procedure was repeated for each listener's location.

The results of these calibrations indicated that the frequency response, averaged over the measurements made at the eight seat positions, was within ±2 dB of a flat response for the wide-band random noise excitation. The response at the individual seats for the pure-tone excitation deviated no more than ±6 dB from flat response.

Subjects

The subjects were college students who volunteered and were paid for their participation. The subjects were rejected if they had hearing losses that exceeded 15 dB relative to the audiometric zero given in reference 21. The subjects were also questioned to ensure that they did not have any history of hearing or ear problems. A group of 41 subjects, 30 male and 11 female, was selected from those passing the screening. The ages of the subjects ranged from 17 to 48 with a mean age of 21.

Test Procedure

Prior to the tests, the anechoic chamber was described to each group of subjects. The subjects were cautioned concerning the nature of the wire mesh floor and assured that the level of the noise would not damage their hearing. Subjects were not informed of the specific nature of the noise sources, but were told only that they would be hearing aircraft noises.

Once the subjects were seated in the chamber, instruction and answer sheets were distributed. The subjects were asked to write test identification data on the instruction and answer sheet. (Appendix A shows a sample instruction and answer sheet.) The subjects read the instructions as the test conductor read them aloud. The instructions (see Appendix A) asked the subjects to imagine that they were in or near their home during the day and/or evening and engaged in typical, awake activities. On this basis, the subjects were asked to judge which of the two flyover sounds in each stimulus pair would be more acceptable to them.

Each group of subjects was given half of the test in four 18-minute sections separated by 12-minute rest periods. In each section, the subjects listened to the sounds of 15 stimulus pairs. The second half of the test, also consisting of four 18-minute sections separated by 12-minute rest periods, was given from 2 hours to 4 days later, depending upon the availability of the subjects.

RESULTS AND DISCUSSION

Judged Improvement Due to the Nacelle Modification

The results of the judgment test are presented in figures 6(a) to 6(l). Each figure shows the data for one flight condition. The percentage of judgments that the noise of the modified nacelle was more acceptable than the noise of the existing nacelle is represented along the ordinate. The relative amplification of the level of the noise from the modified aircraft is represented along the abscissa. Relative amplification was defined as the difference between (a) the noise level of the modified airplane in the anechoic chamber relative to the actual noise level of the modified airplane, and (b) the noise level of the existing airplane in the anechoic chamber relative to the actual noise level of the existing airplane. The value of the PSE is shown for each of the 12 conditions as the value of the relative amplification corresponding to the 50-percent point.

In interpreting the meaning of raising the noise level of the modified aircraft, it is necessary to understand something about the nature of the rating scales tested. Noise-rating scales have either a fixed frequency weighting or slightly varying weightings which, for changes in sound level not exceeding 15 dB, can be considered fixed weightings. Therefore, raising or lowering the spectrum of a flyover equally at all frequencies, within a limit of 15 dB, would change all rating-scale data by an amount equal to the change in level. In addition, the nature of tone-correction and duration-correction factors in current use is such that uniform changes of the entire spectrum have no effect on the magnitude of the correction factors. Thus, the change in the level of the noise from the modified airplane relative to the level of the noise from the existing airplane shown in figure 6, while reported in dB, has the same numerical value on all of the noise rating scales studied.

Figure 7(a) summarizes the PSE data (i.e., the judged improvements) from figure 6, while figure 7(b) shows the differences between judged and calculated improvements. The calculated improvement for this case was defined as the difference between the EPNL of the existing airplane and the EPNL of the modified airplane. The EPNL's for these calculations were those listed in table I. The results shown in figures 7(a) and 7(b) are given in terms of EPNL because the calculated noise reductions shown in reference 4 were in terms of this quantity.

Over the range of heights from 450 to 2800 ft, the judged improvement in the acceptability of the sound heard outdoors [based on the faired lines in figure 7(a)], varied from approximately 11 to 14 EPNdB at the landing-approach power setting, from approximately 4 to 13 EPNdB at the reduced-climb-gradient power setting, and from approximately 4 to 7 EPNdB at the takeoff power setting. The magnitude of the judged improvements in the sound from the indoor noise recordings was somewhat less than the magnitude of the judged improvement in the sound from the outdoor noise recordings.

The faired lines in figure 7(b) indicate that the judged improvements were on the average approximately 2 EPNdB greater than the calculated improvements. The reduction in generalized EPNL at the landing-approach power setting (see fig. 51 of ref. 4) ranged from approximately 9 to 12 EPNdB at locations under a 3-degree landing-approach flight path for the same range of heights.

Assuming a 3-degree landing-approach glideslope, the distances from the landing threshold which correspond to the range of heights from 450 to 2800 feet are approximately from 1.4 to 9 nautical miles. Thus, it would be reasonable to conclude that the range of reductions in the landing noises from individual DC-8-50/61 type aircraft which would be heard outdoors under the flight path was well represented in this test. Due to the selective attenuation of high-frequency noise with distance, the magnitude of the noise reductions experienced at locations to the side of the flight path will decrease with distance to the side.

The effect of modifying the nacelles of existing airplanes would be to produce the stated noise reductions for a portion of the total aircraft landings at any given airport. Assessment of the subjective reaction to the reduction of these landing-approach noises when combined with the landing-approach noises of various non-retrofitted aircraft and new-generation aircraft plus the takeoff noises of these various aircraft was beyond the scope of this study.

Noise-Rating Scales

The results of the judgment tests were analyzed to determine the relationship between the judgment data and predictions of the judged improvements, as calculated according to the eight noise-rating scales. The rating-scale data were obtained from analysis of the 24 recordings using parallel 1/3-octave-band filters. The dynamic response of the data reduction system approximated that of a precision sound level meter set to "slow." The SPL's were sampled at 0.5-second intervals. The data were processed by a digital computer to calculate values for each of the eight noise-rating scales.

Figures 8(a) through 8(h) compare judged improvements to improvements calculated using each of the eight noise-rating scales. If the noise-rating scale were a perfect predictor of the judgments, there would be a one-for-one correspondence between judged and calculated improvements and all data points would fall on the 45-degree line through the origin shown by the solid line in each figure. A data point above the 45-degree line indicates that, for this test condition, the improvement determined from the judgments was greater than the improvement determined from the rating-scale calculations.

The dashed line in each figure is, by definition, a 45-degree line whose intercept on the ordinate is equal to the mean difference between judged and calculated improvements. If the data fell exactly on this line, the standard deviation of the differences would be zero; i.e., only a constant difference would occur between the judged and calculated data. The mean difference was shown because of its frequent inclusion in psychoacoustic literature.

Tabulated values of the statistical relationships between the judged and the calculated improvements for the various noise-rating scales are given in table II. The column labeled as the standard deviation of differences presents the standard deviation of the differences between the judged and the calculated improvements. The standard deviation of the differences is a measure of the scatter of the data around the dashed lines in figure 8. Four scales [dB(D), PNLM, LL, and dB(A)] had nearly the same, relatively small scatter. The three scales PNLTM, EPNL, and PNLM + D had similar but slightly greater scatter. The dB(C) scale had a scatter that was significantly larger than that of any other scale.

The column labeled mean difference provides the average error data for each scale. Since the judged improvements were mainly due to changes in tone amplitude, the mean difference reflects the adequacy of the scales in accounting for tones. PNLTM and EPNL, the two tone-corrected scales, have the smallest mean differences. The three sound level scales are ranked in the order dB(D), dB(A), and dB(C), reflecting the relative emphasis placed by the frequency weightings on the high-frequency portion of the spectrum where the tones occurred.

It appears, therefore, that a tone-correction factor is required to provide adequate emphasis on the tonal components, but that the addition of the tone-correction factor increases the standard deviation of differences. Addition of duration-correction factor to PNLTM and PNLM (producing EPNL and PNLM + D, respectively) increased both the mean and the standard deviation of the differences.

The total standard errors of estimate in table II provide a figure of merit based upon the mean difference and the standard deviation of the differences. These values also provide the best prediction of the ability of a noise-rating scale to correctly estimate judgment data. The total standard error of estimate was defined as the root mean square of the mean difference and the standard deviation of the differences; i.e., $[(\text{mean difference})^2 + (\text{standard deviation of differences})^2]^{1/2}$. The total standard error of estimate was the quantity used to order the rating scales in table II and in figure 8.

The significance of the total standard error of estimate is that approximately 67 percent of the data would be expected to fall within one standard error, 95 percent within two standard errors, and 99 percent within three standard errors. For example, for the PNLTM rating scale, 67 percent of the calculated improvements would be expected to fall within 2.4 PNdB of the judged improvements.

Although the data given in table II indicate that there were differences in the ability of the various scales to predict judgment data, the statistical significance of the differences cannot be determined from the data in table II. An analysis was conducted to determine the degree of confidence that could be placed in the ordering of the noise-rating scales and in the ability of the scales to predict the judgment data. To this end, correlation coefficients were determined between the values of the calculated improvements according to each of the eight rating scales, and between the differences between the judged and the calculated improvements (i.e., between the scale errors).

The correlation coefficients between the calculated improvements are given in table III(a). These coefficients were high (from 0.80 to 0.98) for all scales except dB(C). This result indicates that seven of the eight scales yielded similar ratings of the acceptability of the sounds. The calculated improvements for the dB(C) scale did not correlate well with the calculated improvements for any of the other scales. This result was not surprising since C-weighted sound level was known to have little relationship to human response.

The correlation coefficients between the scale errors are given in table III(b). The coefficients were similar in value and notably high. This result indicates that the eight scales tended to yield the same errors between judged and calculated improvements.

The statistical significance of the difference between the accuracy of the noise-rating scales as indicated by the standard errors of estimate in table II was investigated by application of Student's t-test for correlated data.

The test is a statistical method that may be used to obtain a probability statement concerning two sets of data belonging to the same or different distributions. In many empirical studies, chance factors such as sampling and random changes may yield differences. Assuming a normal (or nearly normal) distribution, examination of the overlap in the sets of data permits making a statement concerning whether the difference between the two sets of data could have occurred by chance alone or whether there are probably two separate sets of data. (For a further discussion of this application of the test, see ref. 22.) The results of this analysis are given in table IV. The probability was less than 90 percent that the standard errors of estimate for the five best scales [PNLTM, dB(D), PNLM, EPNL, and LL] were different. The remaining three scales [PNLM + D, dB(A) and dB(C)] were significantly different from one another and also significantly different from the five best scales in the majority of cases.

Detailed Statistical Analyses

Detailed statistical analyses (described in Appendix B) were performed to determine the separate components of the total error variance. The components included errors due to the noise-rating scales and to various sources of experimental error. For seven of the eight noise-rating scales, the analyses indicated that experimental error was small enough to permit reasonably accurate determination of scale accuracy. For the eighth scale, PNLTM, the total error variance was small and the error variance due to stimulus presentation was so large compared to the total error variance that a reliable estimate of scale error variance could not be obtained. The error variance in stimulus presentation was by far the major cause of experimental error for all eight scales.

For two of the twelve operational conditions in figures 8(a) through 8(h), there was a consistent difference between the judged improvement and the improvements calculated using the eight rating scales. For the reduced-climb-gradient thrust condition at 1000 feet, outdoors (the squares with the largest judged improvement), the data are consistently above and to the left of the majority of data points. For this condition, the judged improvement was considerably in excess of the expected improvement. The average calculated improvement for the eight rating scales was 7 units less than the judged improvement. The data points for the indoor noise recordings of the noise at the reduced-climb-gradient thrust were consistently below and to the right of the majority of the data in figure 8. All test results were carefully reviewed to ensure that there were no measurement, calculation, or operational errors. No evidence was obtained that would suggest modification or deletion of the data points for these two conditions.

CONCLUSIONS

For the conditions of this experiment, the data support the following conclusions:

1. The nacelle modifications to the DC-8-50/61 aircraft resulted in improvements in the subjective response to aircraft noise throughout the operational conditions tested. The approximate improvements for flyovers recorded outdoors (depending upon aircraft height) ranged from 11 to 14 EPNdB for landing-approach thrust; from 4 to 13 EPNdB for the reduced-climb-gradient thrust; and from 4 to 7 EPNdB for takeoff-rated thrust. Improvements for indoor listeners were approximately 4.5 EPNdB for takeoff-rated thrust at a height of 1500 feet, approximately 5.5 EPNdB for reduced-climb-gradient thrust at a height of 2500 feet, and approximately 8.5 EPNdB for landing-approach thrust at a height of 450 feet.

2. Of the eight noise-rating scales evaluated in this study, PNLTM, dB(D), PNLM, EPNL, and LL provided the best agreement between scale data and judgment data. These five scales were not significantly different from one another statistically, but did differ from the other three scales. Improvements predicted from scale data were generally slightly smaller than the judgment data. The noise measurement data included in reference 4, which are reported in EPNL, appear to be reasonably correct representations of judged improvements.

Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, California March 1970

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APPENDIX A

SAMPLE INSTRUCTION AND ANSWER SHEET

This appendix presents a sample of the instruction and answer sheets given to the subjects. The sheet provides space for responses to the 15 flyover stimulus pairs presented in one 18-minute test section.

Name	Group	Tape	Date

Circle A if first sound is more acceptable.
Circle B if second sound is more acceptable.

INSTRUCTIONS:

The primary purpose of the tests being conducted is to determine, if possible, how people feel about the relative acceptability of one type or level of aircraft noise when compared with a second type or level of aircraft noise.

You will hear a series of sounds from aircraft. The sounds will occur in "pairs" and your task is to judge which sound in each pair you think would be more acceptable to you if heard in or near your home during the day and/or evening when you are engaged in typical, awake activities.

After you have heard each pair of sounds, please quickly decide which of the two you feel would be more acceptable to you. If you think the second sound of a pair would be more acceptable, circle B for that particular pair. If you think the first sound in the pair would be more acceptable to you than the second, circle A.

Please concentrate on the judgment at hand and give an answer even though the two sounds may seem approximately equal in acceptability to you. If you feel that there is absolutely no real difference in terms of acceptability of the two sounds, please circle either A or B, giving the best guess you can, and put a question mark after that pair.

There are no "right" or "wrong" answers, nor do we expect people to agree with each other. We are interested in how you feel about the sounds and how people differ in their judgments of the acceptability of these aircraft sounds.

An announcement of the item number will be made before each pair of sounds is to occur. The sounds of a pair will be separated by a few seconds. During the test period, which will be approximately 18 minutes, please remain quiet and attentive. Give us your best judgment and imagine, if you will, that you are listening to these sounds in or near your own home.

1.	A	B
2.	A	B
3.	A	B
4.	A	B
5.	A	B
6.	A	B
7.	A	B
8.	A	B
9	A	B
10.	A	B
11.	A	B
12.	A	B
13.	A	B
14.	A	B
15.	A	B

APPENDIX B

DETAILED STATISTICAL ANALYSES

Previously conducted psychoacoustic studies provided no detailed analyses of the sources of experimental error. Thus, it has generally been impossible to distinguish between experimental error and inherent error in the noise-rating scale and thereby obtain a true estimate of the ability of a noise-rating scale to predict human judgments of an attribute of a noise. For the work reported here, an analysis of the statistical variance of the various sources of experimental error and the variance due to errors in the noise-rating scales was conducted to assess the relative magnitudes of the sources of error.

The results of this study of the sources of error are presented in table V. The right half of the table lists the error variances for the four sources and the total error variance associated with the eight noise-rating scales. Variance has the property that the components can be summed to determine the total variance.

The total error variance is the sum of the square of the mean difference between the judged and the calculated improvements and the square of the standard deviation of the differences between judged and calculated improvements: (mean difference)^2 + (standard deviation of differences)^2. These data are presented in table II. The variances in the three components of the experimental error (i.e., the errors due to the method of presenting the stimulus material, the errors due to the method of data reduction, and the errors due to the choice of the subjects) were determined by test and analysis. The variance due to errors in the rating scale was determined by subtracting the variance of the three sources of experimental errors from the total variance.

The error variance due to the choice of the subject population was estimated by partitioning a sample of the judgment data provided by a group of 40 subjects into two equal groups. One of these groups was then further divided into two equal subgroups. Statistical analyses were conducted to determine the variance in the PSE calculations for the pairs of smaller groups. The error variance of the PSE for the group of 40 subjects was then estimated, using standard statistical relationships, from the error variance of the PSE based on the two groups of 20 subjects and the error variance of the PSE based on the two groups of 10 subjects. The resulting error variance of 0.2 units shown in table V was the same for all noise-rating scales because the test method yielded PSE determinations which were independent of the choice of the noise-rating scale.

The error variance in the calculated improvements due to the data-reduction system used to obtain the calculated noise levels was estimated by repeating the analysis of the 18 outdoor flyover-noise signals. The error variance between the two sets of calculations was on the order of 0.5 units and was a result of the errors in repeatability of data-reduction.

The error variance due to stimulus presentation was estimated for four pairs of flyover noise signals by examining the error variance between the calculated noise levels (a) at the output of the tape recorder and (b) in the anechoic chamber at three of the eight seat positions. The error variance due to the method of stimulus presentation alone was then calculated by subtracting the error variance attributable to data reduction from the estimated error variance due to stimulus presentation described above.

Because a sample of only 4 of the 12 stimulus pairs and only 3 of the 8 seat positions was utilized for the assessment of error variance due to stimulus presentation, the assessment may not be accurate. For the PNLTM scale, the estimated error variance of stimulus presentation was too large, while for the PNLM + D scale, the error variance of stimulus presentation appeared to be too small. It is estimated that the error variances for the stimulus presentation could be incorrect by as much as ±2 units.

The standard errors of estimate corresponding to the error variances are listed in the left half of table V. The standard errors of estimate were determined by taking the square root of the respective error variances. The standard errors of estimate have the property of defining confidence intervals which can be placed around the data. From the data in table V, it can be seen that experimental error was small relative to scale error except in the case of PNLTM, and that even in this case stimulus presentation was the only important source of error.

TABLE I. – FLIGHT CONDITIONS AND EPNL VALUES FOR THE FLYOVER NOISE RECORDINGS

Location for tape recordings	Nacelles	Referred installed net thrust, lb	Height overhead, ft	EPNL[a], EPNdB
Recordings under the landing-approach flight paths				
Outdoors	Existing	4700	507	111.4
Outdoors	Modified	4600	521	99.7
Outdoors	Existing	5000	1179	103.5
Outdoors	Modified	4500	1384	89.9
Outdoors	Existing	4900	2779	94.6
Outdoors	Modified	4500	2802	85.2
Indoors	Existing	4750	435	96.2
Indoors	Modified	4750	471	82.9
Recordings under the reduced-climb-gradient takeoff flight paths				
Outdoors	Existing	10 400	556	116.3
Outdoors	Modified	10 200	532	105.7
Outdoors	Existing	10 500	1229	108.8
Outdoors	Modified	10 550	1211	100.8
Outdoors	Existing	10 800	2441	101.3
Outdoors	Modified	11 000	2340	97.9
Indoors	Existing	10 500	2860	86.3
Indoors	Modified	10 750	2311	79.4
Recordings under full-thrust takeoff flight paths				
Outdoors	Existing	14 800	530	118.3
Outdoors	Modified	14 100	481	114.6
Outdoors	Existing	14 750	1014	113.8
Outdoors	Modified	14 700	980	110.1
Outdoors	Existing	14 400	2066	105.5
Outdoors	Modified	14 500	2105	104.9
Indoors	Existing	14 800	1758	92.6
Indoors	Modified	14 100	1443	89.9

[a]EPNL's were determined by Stanford Research Institute from the flyover noise recordings on the psychoacoustic test tapes.

TABLE II. – STATISTICAL RELATIONSHIP BETWEEN JUDGED AND CALCULATED IMPROVEMENTS FOR VARIOUS NOISE RATING SCALES

Rating scale	Total standard error of estimate (a)	Mean difference (a)	Standard deviation of differences (a)
PNLTM	2.4	−0.4	2.4
dB(D)	2.6	+1.8	1.9
PNLM	2.6	+1.9	1.8
EPNL	2.9	+1.1	2.7
LL	3.1	+2.7	1.5
PNLM + D	3.6	+2.5	2.7
dB(A)	4.5	+4.1	1.9
dB(C)	7.3	+5.6	4.7

[a]All values are in the units of the corresponding noise-rating scales.

TABLE III. – CORRELATION COEFFICIENTS

(a) Correlation between calculated improvements in flyover noise level for various noise rating scales

	PNLTM	dB(D)	PNLM	EPNL	LL	PNLM + D	dB(A)
dB(D)	0.94	–	–	–	–	–	–
PNLM	0.95	0.98	–	–	–	–	–
EPNL	0.92	0.90	0.91	–	–	–	–
LL	0.86	0.96	0.95	0.80	–	–	–
PNLM + D	0.92	0.89	0.90	0.97	0.81	–	–
dB(A)	0.88	0.98	0.95	0.88	0.94	0.87	–
dB(C)	0.30	0.34	0.40	0.37	0.34	0.49	0.32

(b) Correlation between differences between judged and calculated improvement in flyover noise level for various noise rating scales

	PNLTM	dB(D)	PNLM	EPNL	LL	PNLM + D	dB(A)
dB(D)	0.70	–	–	–	–	–	–
PNLM	0.71	0.72	–	–	–	–	–
EPNL	0.72	0.65	0.73	–	–	–	–
LL	0.26	0.59	0.74	0.30	–	–	–
PNLM + D	0.48	0.51	0.79	0.89	0.54	–	–
dB(A)	0.42	0.73	0.79	0.63	0.73	0.70	–
dB(C)	0.18	0.18	0.68	0.43	0.65	0.73	0.55

TABLE IV. – SIGNIFICANCE[a] OF DIFFERENCE BETWEEN STANDARD ERRORS OF ESTIMATE FOR VARIOUS NOISE-RATING SCALES AS DETERMINED BY STUDENT'S t TESTS FOR CORRELATED DATA

	PNLTM	dB(D)	PNLM	EPNL	LL	PNLM + D	dB(A)
dB(D)	0.24	–	–	–	–	–	–
PNLM	0.24	0.01	–	–	–	–	–
EPNL	0.83	0.52	0.59	–	–	–	–
LL	0.80	0.73	0.88	0.20	–	–	–
PNLM + D	1.44	1.26	1.78	1.48	0.56	–	–
dB(A)	2.29	2.73	3.08	1.83	1.77	1.02	–
dB(C)	4.22	3.94	5.29	3.62	3.95	3.47	0.85

[a]The statistical significance of the t values in this table is that there is a 90 percent probability that the standard errors of estimate for any two noise-rating scales are different when t = 1.37. The probability would be 95 percent for t = 1.81, and 99 percent for t = 2.76.

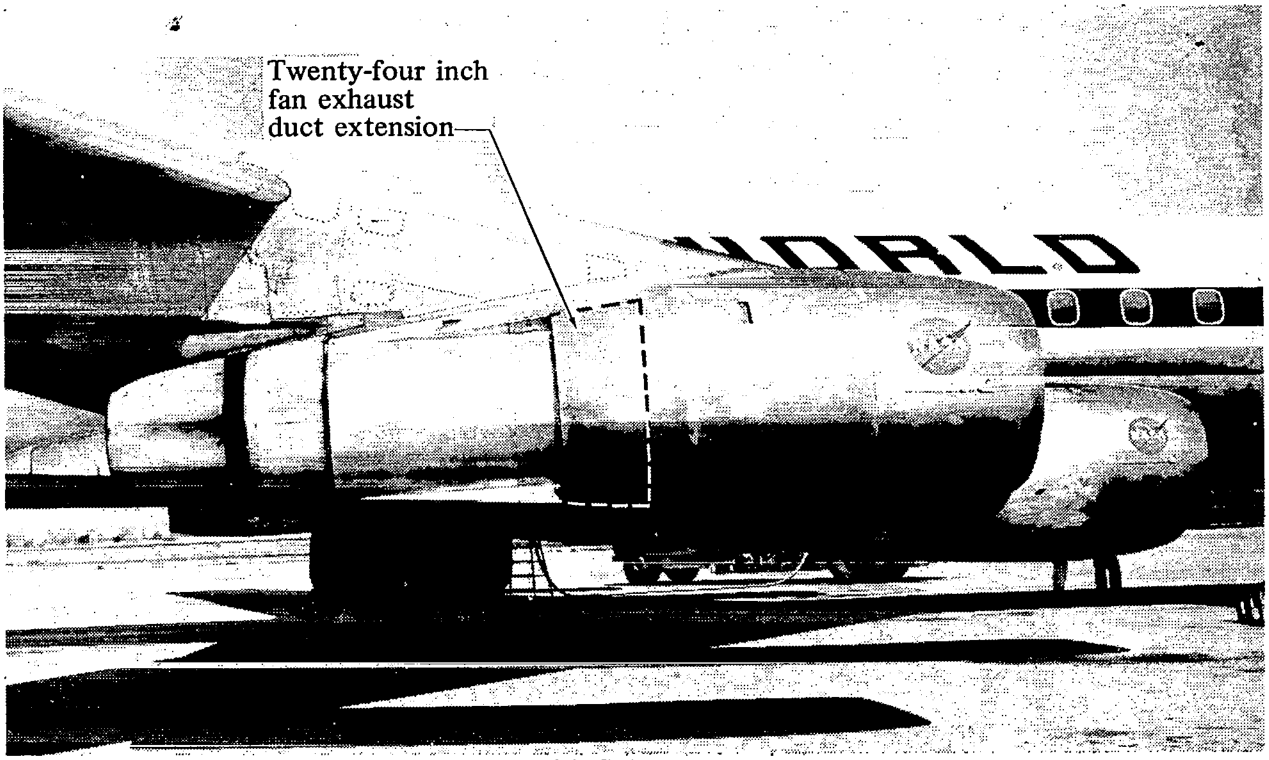
TABLE V. – STANDARD ERRORS OF ESTIMATE AND ERROR VARIANCES FOR VARIOUS NOISE-RATING SCALES[a]

Noise-rating scale	Standard errors of estimate					Error variances				
	Total	Stimulus presentation	Data reduction	Subjects	Rating scale	Total	Stimulus presentation	Data reduction	Subjects	Rating scale
PNLTM	2.4	(b)	0.8	0.4	(c)	5.8	(b)	0.6	0.2	(c)
dB(D)	2.6	1.6	0.8	0.4	1.8	6.8	2.5	0.7	0.2	3.4
PNLM	2.6	1.9	0.7	0.4	1.6	6.8	3.5	0.5	0.2	2.6
EPNL	2.9	1.0	0.6	0.4	2.6	8.4	1.0	0.4	0.2	6.8
LL	3.1	1.3	0.5	0.4	2.7	9.6	1.7	0.3	0.2	7.4
PNLM + D	3.6	0.3[b]	0.6	0.4	3.5	13.0	0.1[b]	0.4	0.2	12.3
dB(A)	4.5	1.8	0.6	0.4	4.1	20.3	3.2	0.4	0.2	16.5
dB(C)	7.3	1.0	0.6	0.4	7.2	53.3	1.0	0.4	0.2	51.7

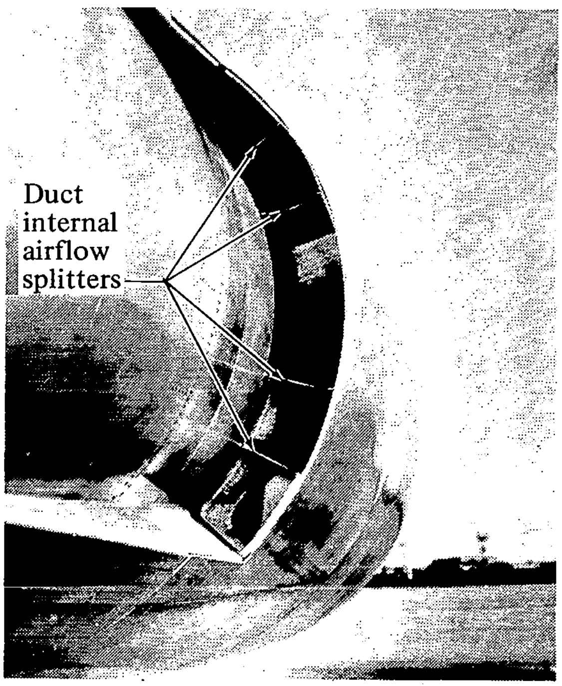
[a]All values in the units of the corresponding noise-rating scales.

[b]Estimate of error and hence error variance of stimulus presentation are probably incorrect due to small sample size.

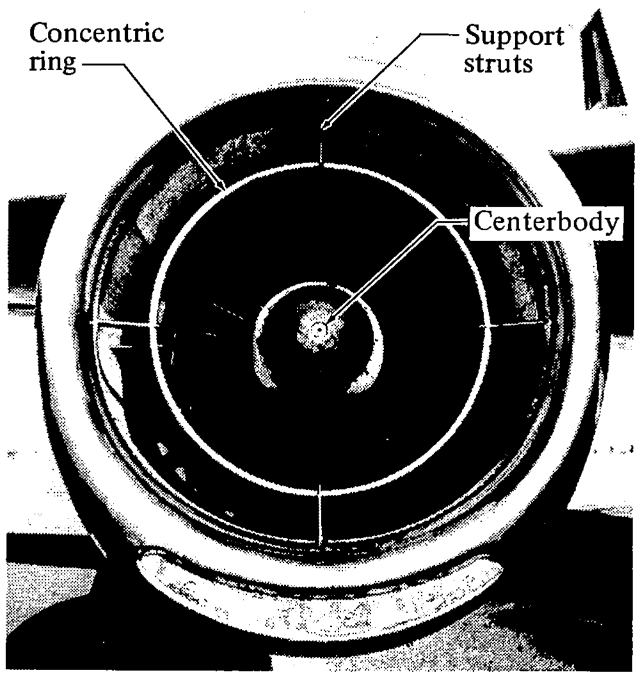
[c]Estimate of error and error variance for noise-rating scale could not be determined, because of incorrect estimate of error for stimulus presentation.



(a) Side view.



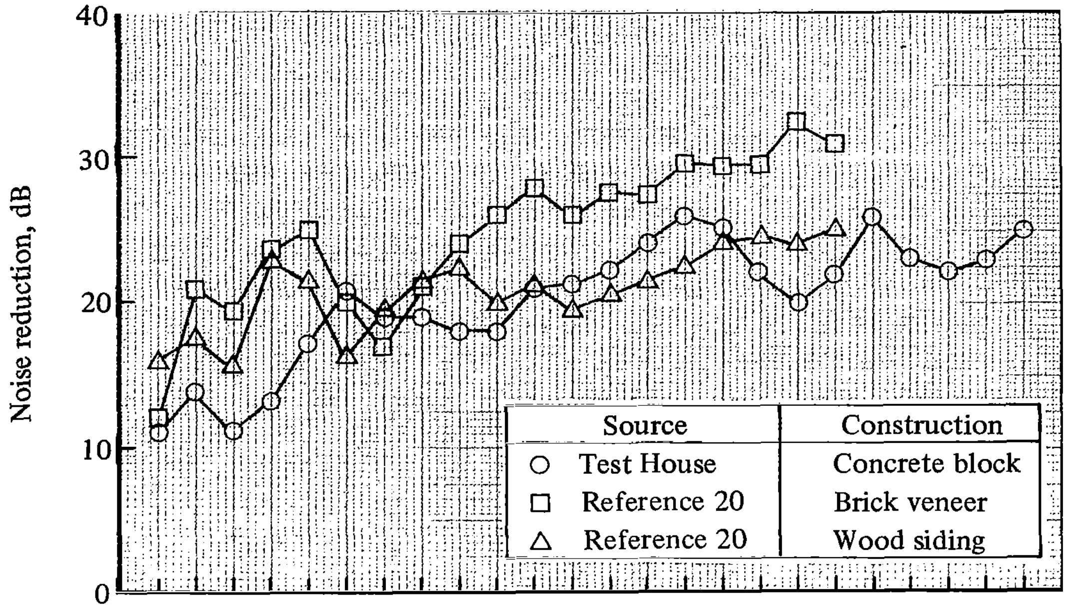
(b) Aft view of fan-exhaust duct.



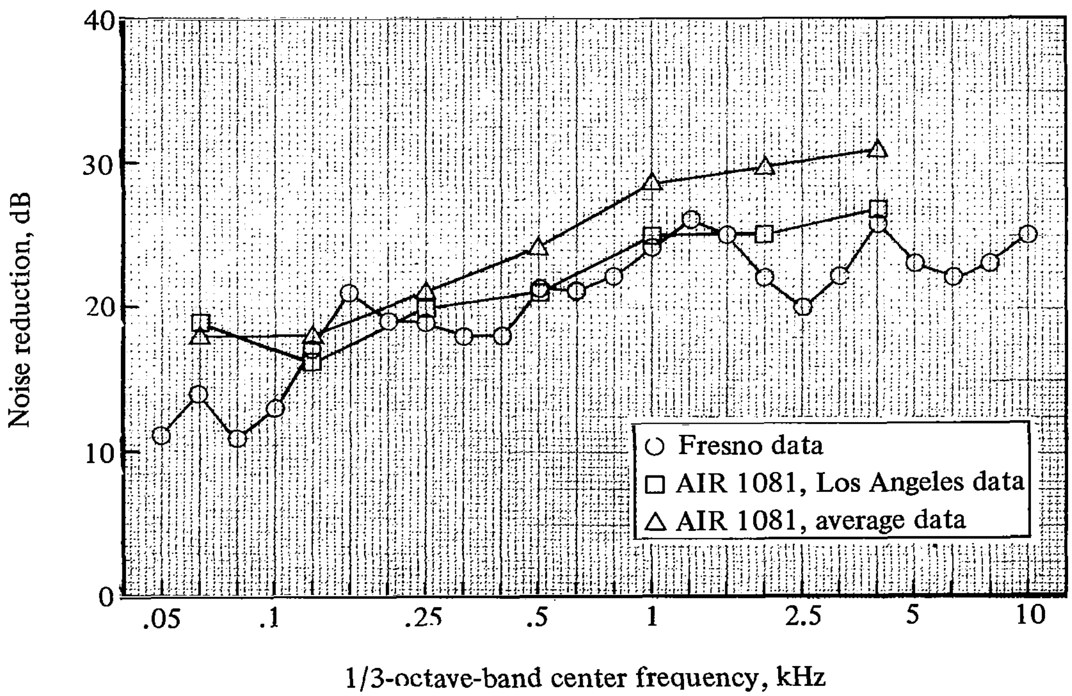
(c) Front view of inlet.

Figure 1. – Test nacelles.

Figure 2. – Test house at Fresno.

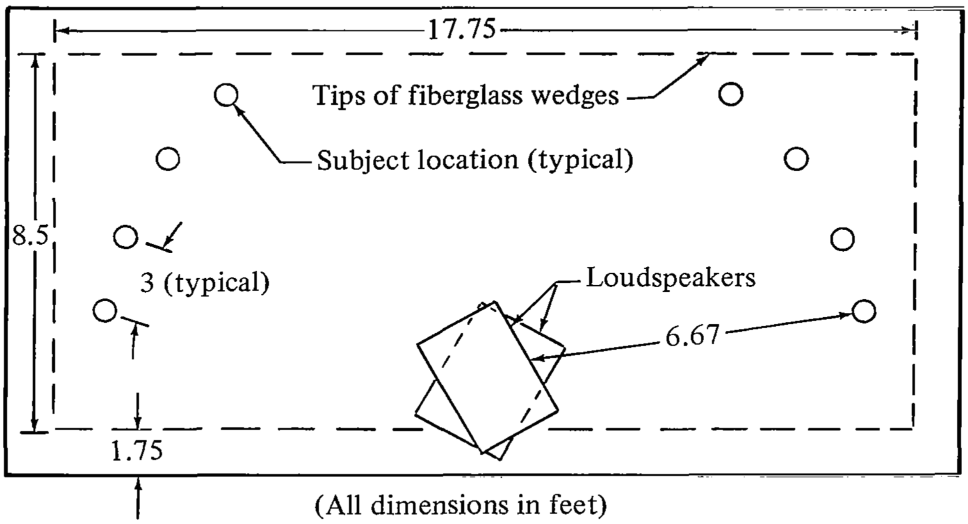


(a) Comparison of results obtained at Fresno and in reference 20.



(b) Comparison of results obtained at Fresno to data in proposed SAE AIR 1081.

Figure 3. – House noise-reduction data for windows – closed conditions.



(All dimensions in feet)

Figure 4. – Plan view of anechoic chamber.

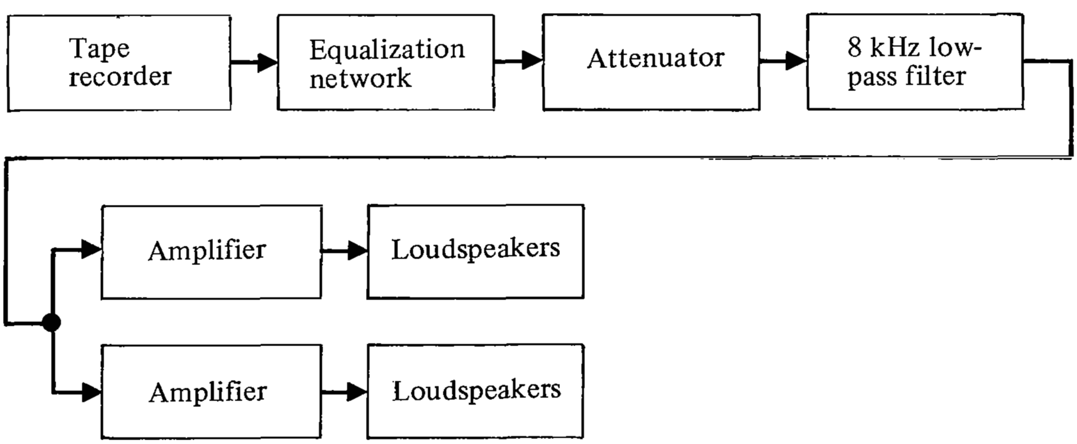
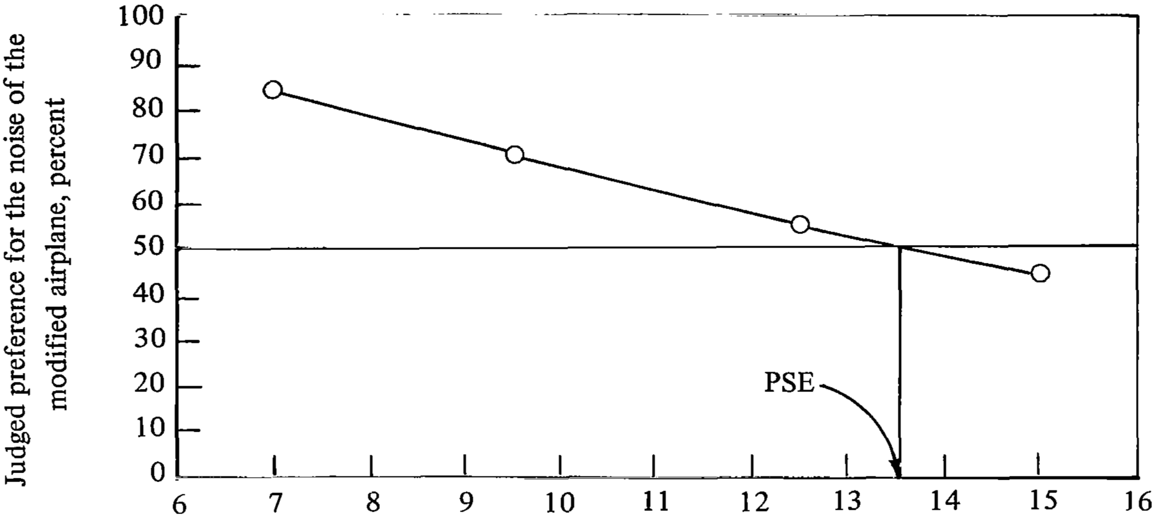
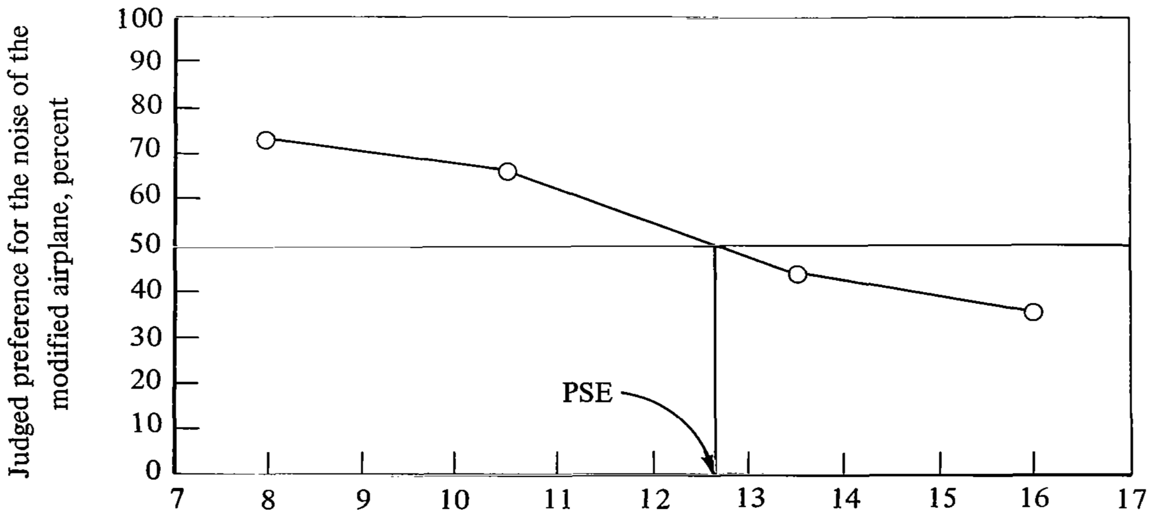


Figure 5. – Block diagram of instrumentation for stimulus presentation.



Relative increase in the noise level of the modified airplane, dB

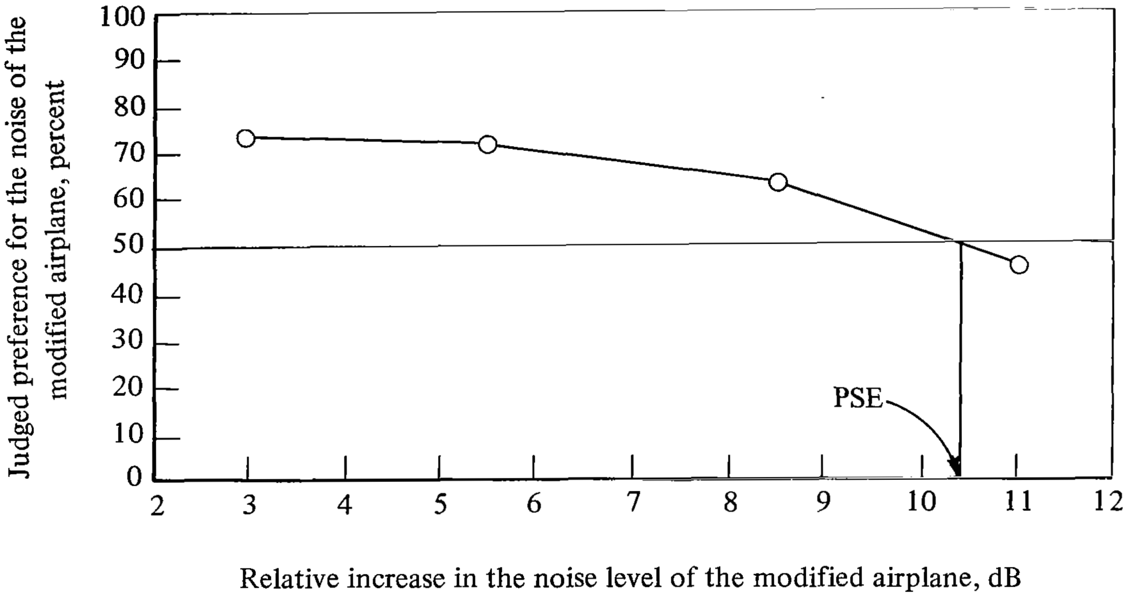
(a) Test condition for 500-ft height, outdoors, landing-approach thrust.



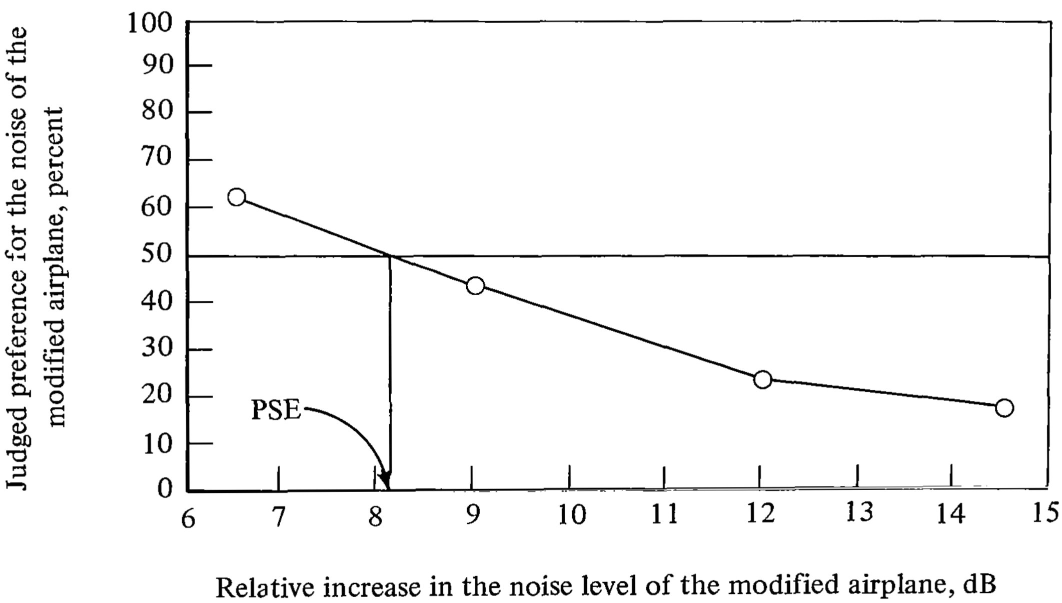
Relative increase in the noise level of the modified airplane, dB

(b) Test condition for 1000-ft height, outdoors, landing-approach thrust.

Figure 6. – Judgment data.

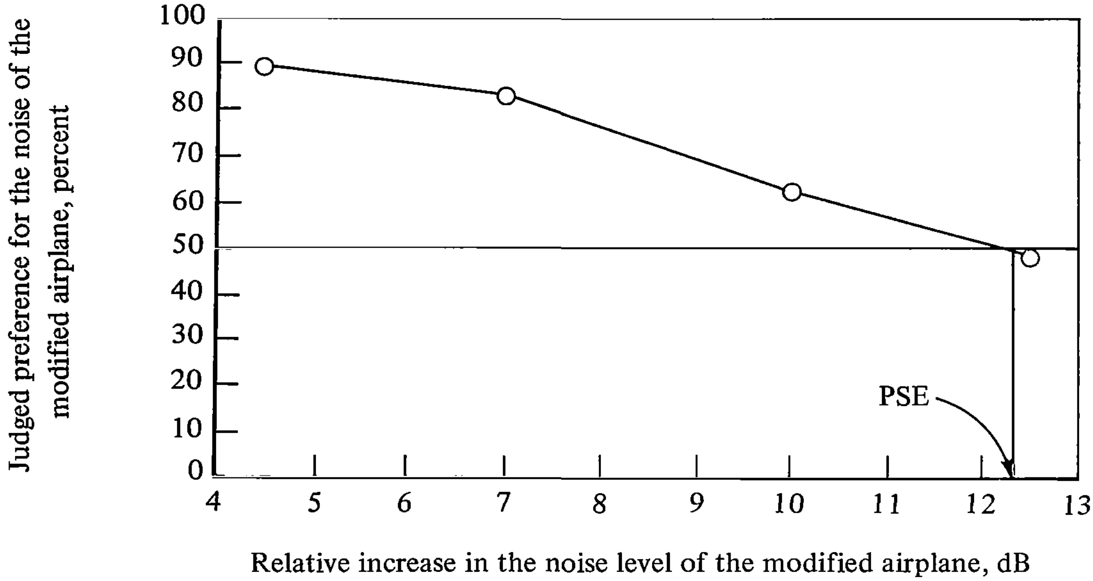


(c) Test condition for 2500-ft height, outdoors, landing-approach thrust.

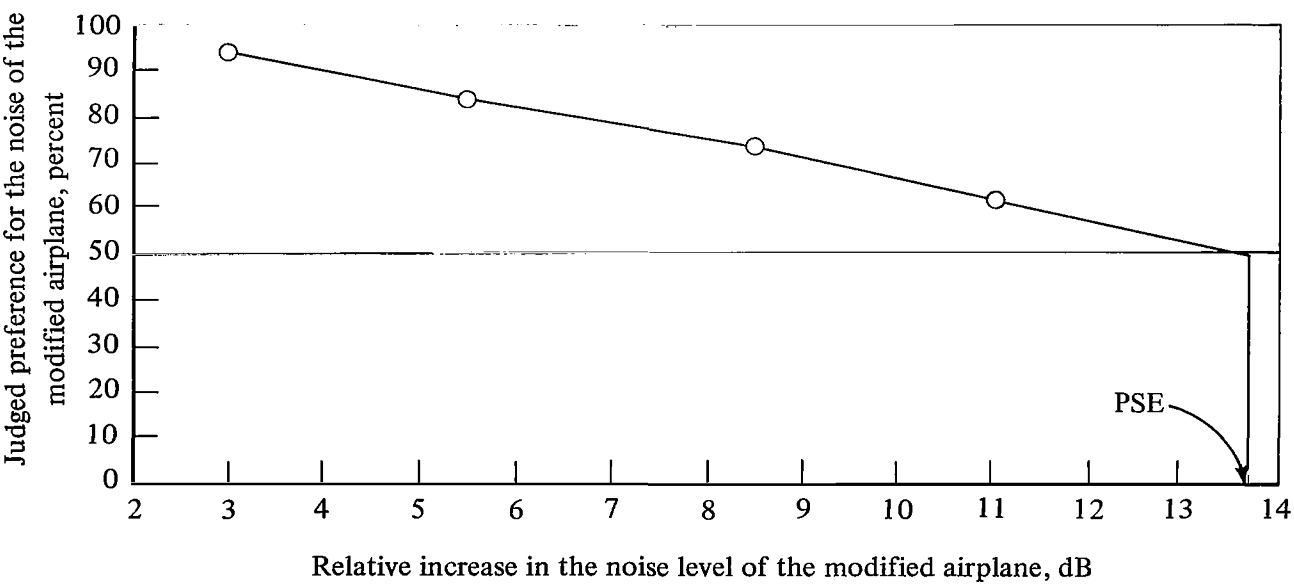


(d) Test condition for 500-ft height, indoors, landing-approach thrust.

Figure 6. – Continued.

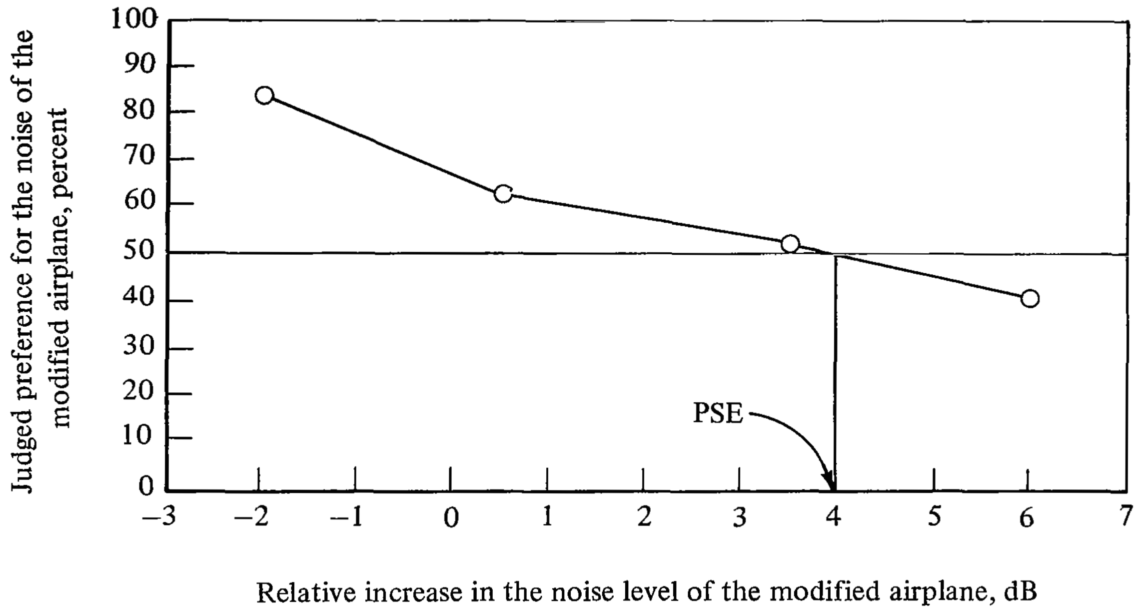


(e) Test condition for 500-ft height, outdoors, reduced-thrust takeoff.

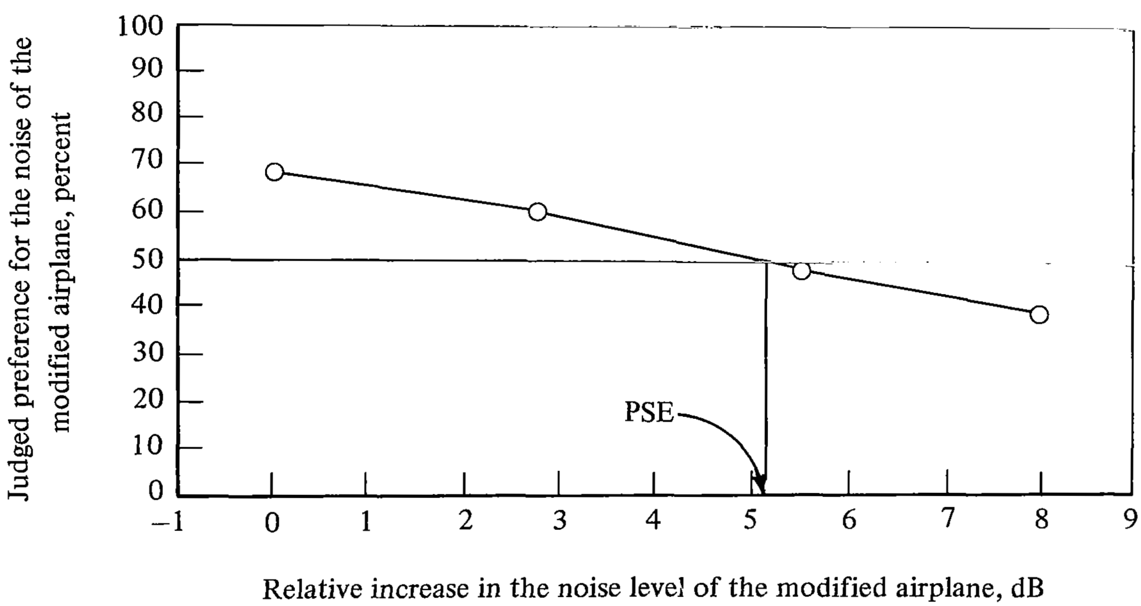


(f) Test condition for 1000-ft height, outdoors, reduced-thrust takeoff.

Figure 6. – Continued.

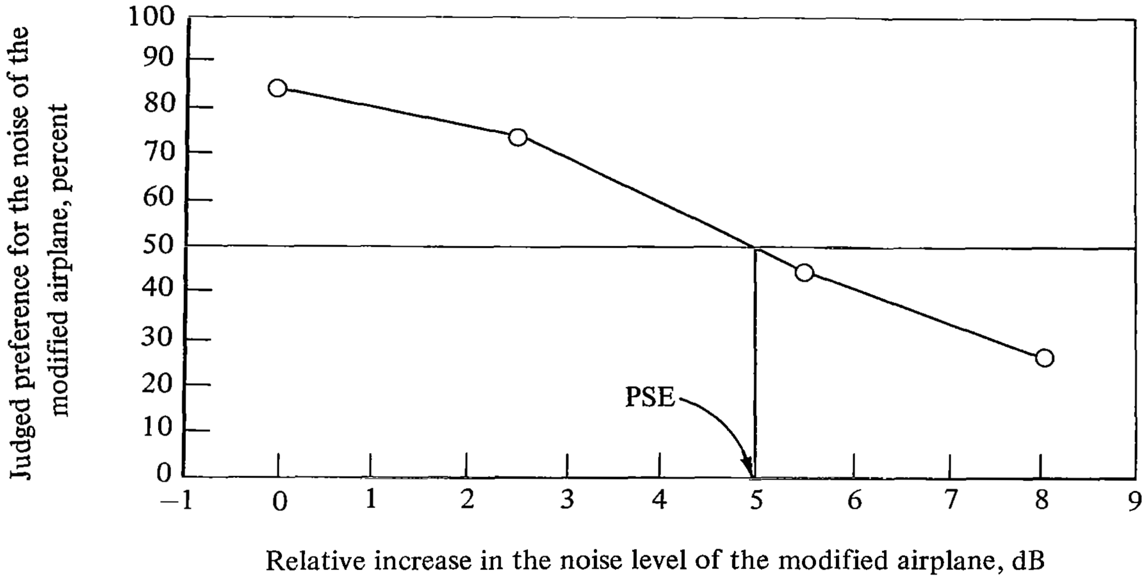


(g) Test condition for 2500-ft height, outdoors, reduced-thrust takeoff.

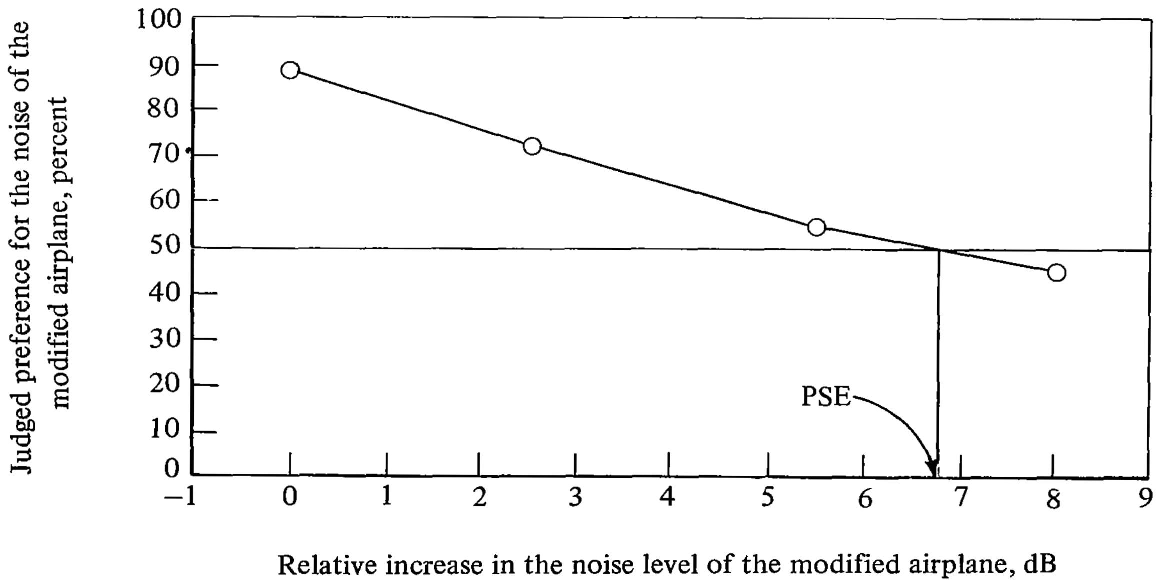


(h) Test condition for 2500-ft height, indoors, reduced-thrust takeoff.

Figure 6. – Continued.

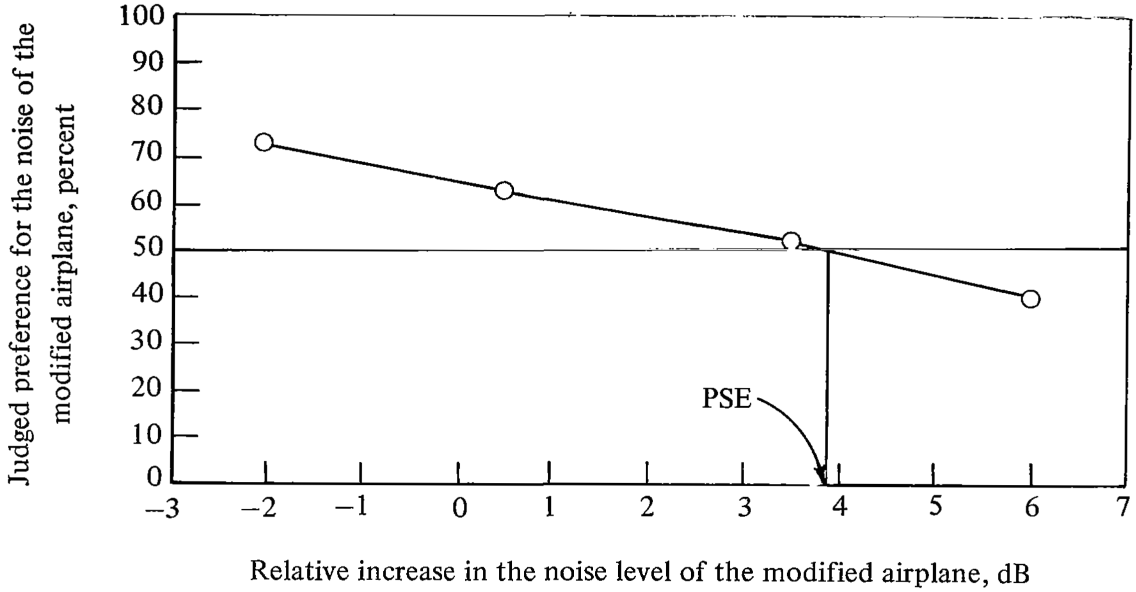


(i) Test condition for 500-ft height, outdoors, takeoff-rated thrust.

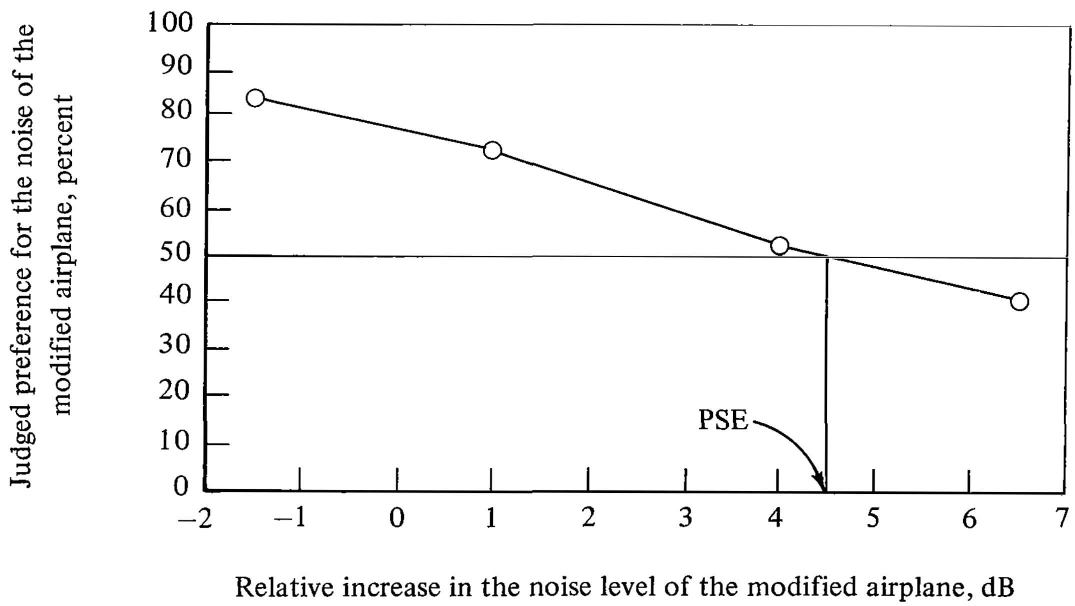


(j) Test condition for 1000-ft height, outdoors, takeoff-rated thrust.

Figure 6. – Continued.

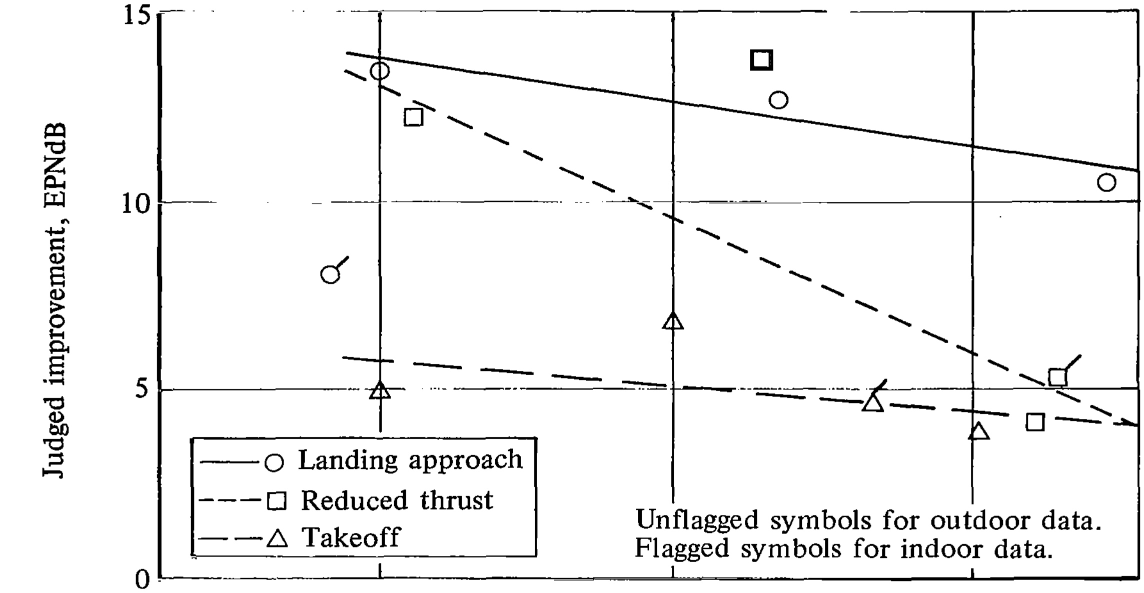


(k) Test condition for 2500-ft height, outdoors, takeoff-rated thrust.

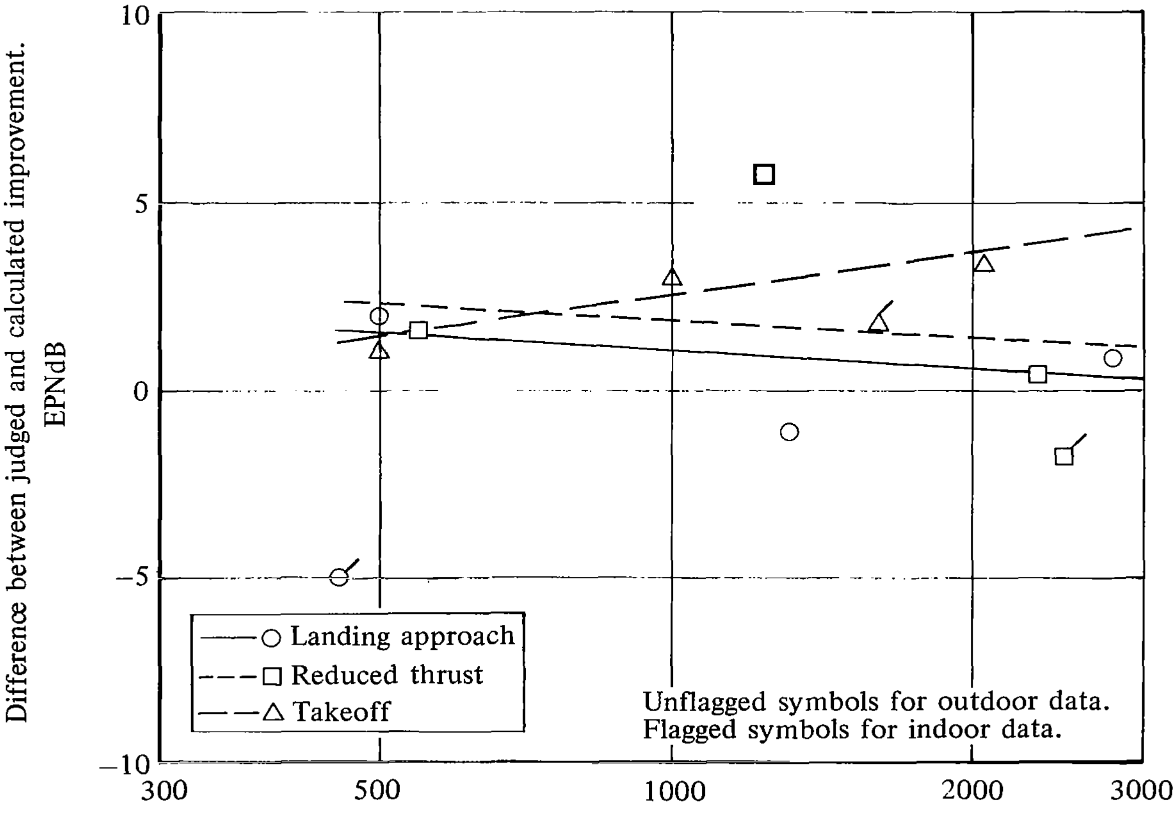


(l) Test condition for 1500-ft height, outdoors, takeoff-rated thrust.

Figure 6. – Concluded.

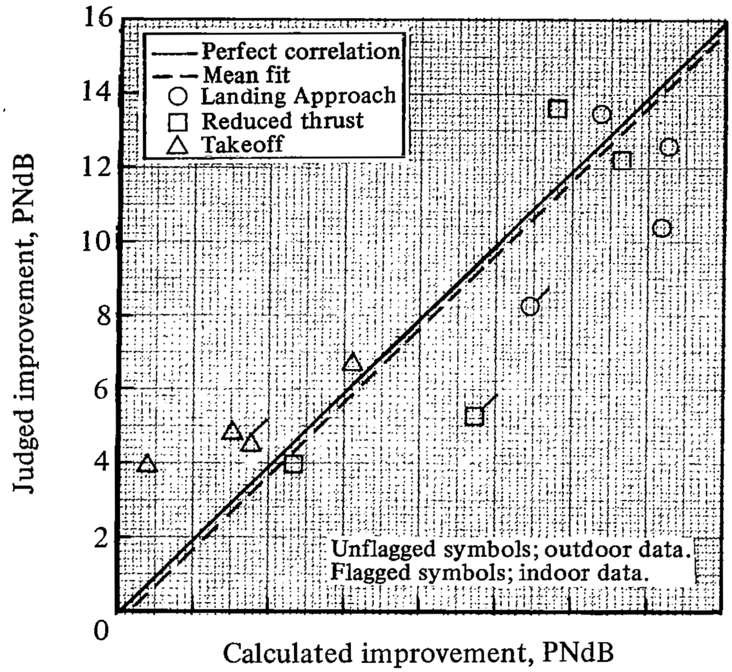


(a) Judged improvements in acceptability of flyover noise due to installation of acoustically treated nacelles.

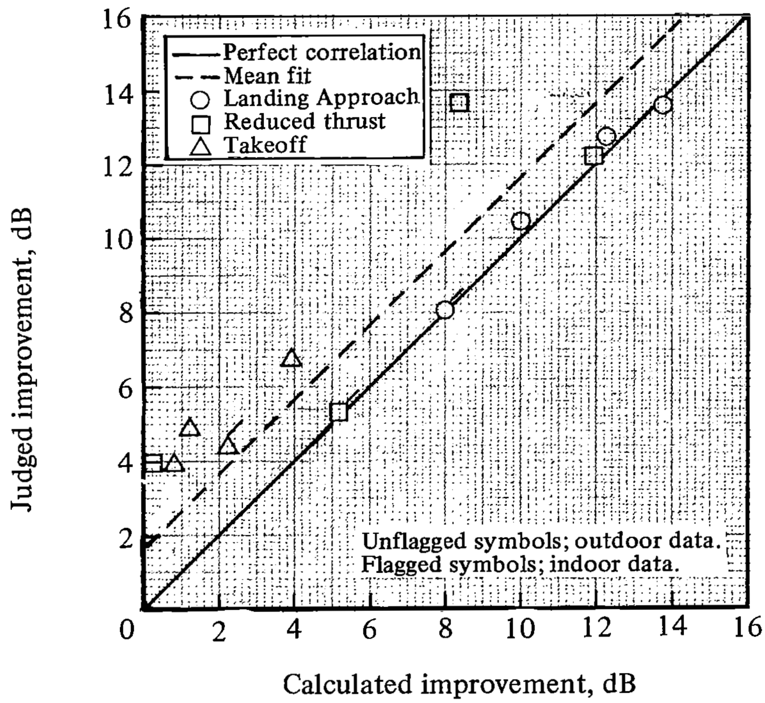


(b) Difference between judged and calculated improvements in acceptability of flyover noise.

Figure 7. – Results of judgment tests of recordings of DC-8 flyover noise with existing and modified nacelles.

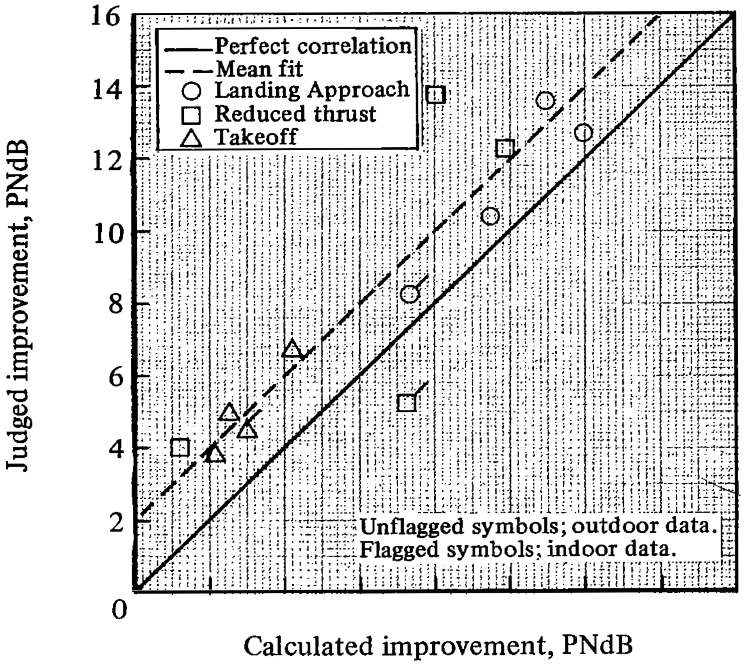


(a) Maximum instantaneous tone-corrected perceived noise level, PNLTM.

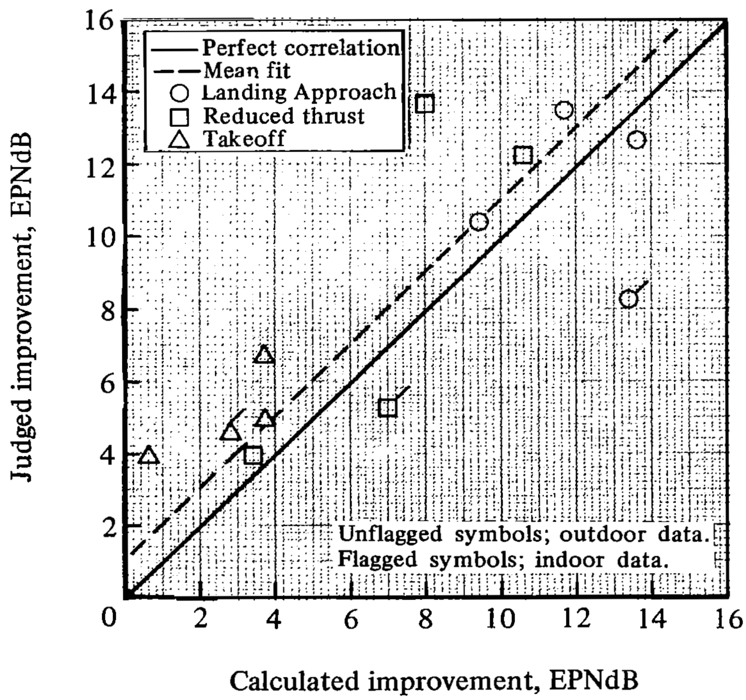


(b) Maximum instantaneous D-weighted sound level, dB(D).

Figure 8. - Comparison of judged and calculated improvements in flyover noise of DC-8 equipped with modified nacelles.

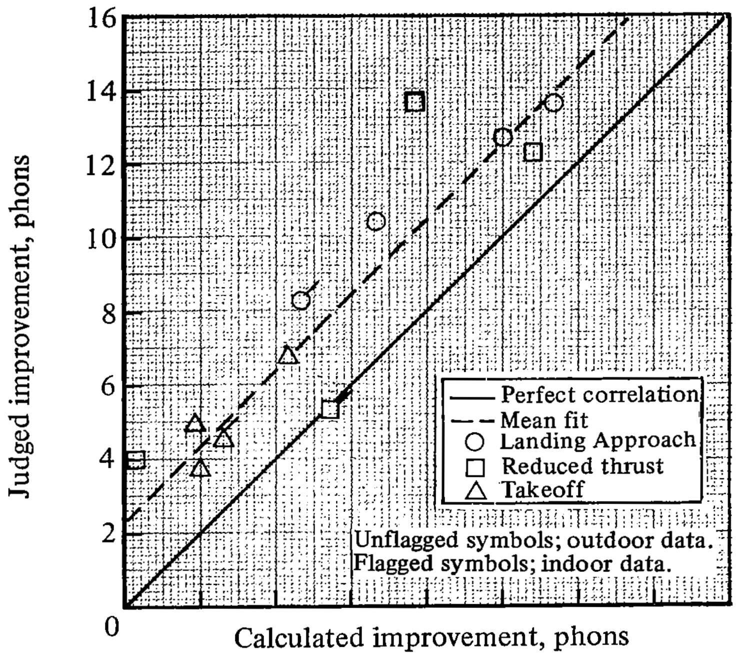


(c) Maximum instantaneous perceived noise level, PNLM.

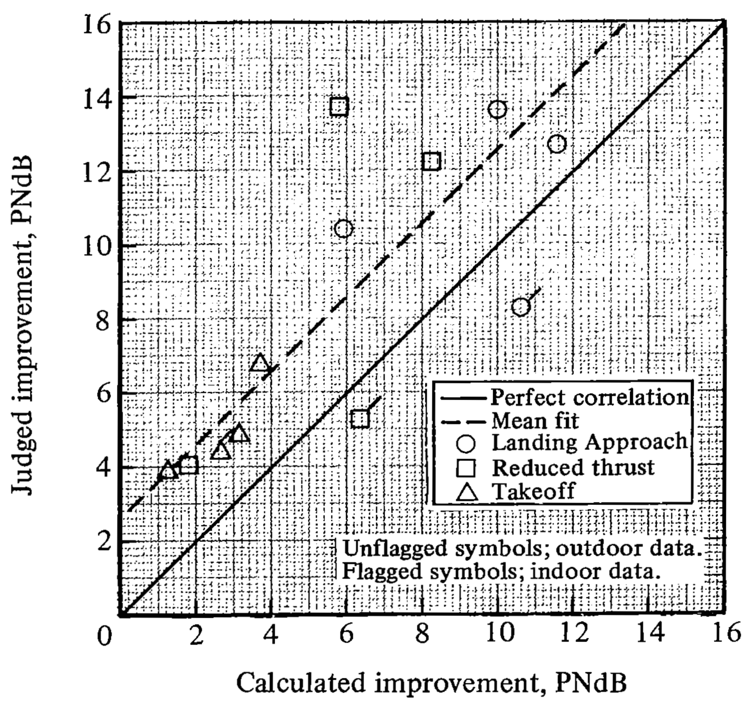


(d) Effective perceived noise level, EPNL.

Figure 8. – Continued.

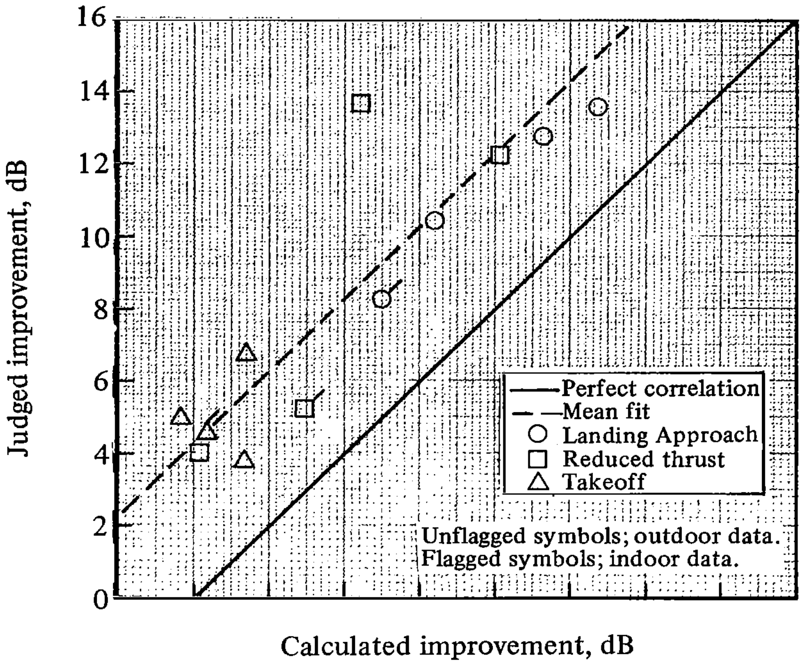


(e) Maximum instantaneous loudness level, LL.

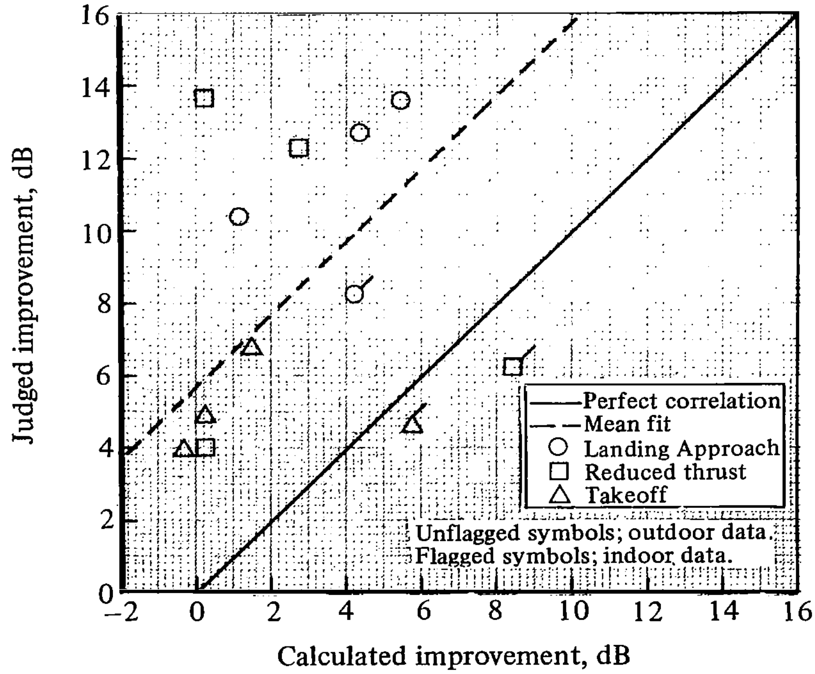


(f) Maximum instantaneous perceived noise level with duration-correction factor, PNLM+D.

Figure 8. – Continued.



(g) Maximum instantaneous A-weighted sound level, dB(A).



(h) Maximum instantaneous C-weighted sound level, dB(C).

Figure 8. – Concluded.